RESEARCH DEPARTMENT

Empirical Acoustic Criterion
Second Report

Report No. B-053/2

1955/12

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

EMPIRICAL ACOUSTIC CRITERION

SECOND REPORT

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CONFIDENTIAL

April 1955

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SUMMARY

Further objective and subjective investigations have been carried out to test the validity of an empirical acoustic criterion. By this means it has been possible to establish for large enclosures an improved version of the original criterion and a new criterion, taking account of volume. A nomogram for the new criterion is included. For small enclosures, such as talks studios, it has been impossible to obtain satisfactory criteria and further investigation is necessary.

1. INTRODUCTION.

In a previous report[1], a tentative empirical acoustic criterion was described which gave good correspondence between a parameter determined by objectively measurable quantities and an individual subjective assessment of studio quality for about 25 enclosures. These 25 enclosures were the only ones for which adequate results were at that time available; it was realised that only extensive use of the tentative criterion could establish or disprove its validity. All that was claimed for this tentative criterion was that it indicated a way in which objective parameters could be combined to estimate subjective quality, on the assumption that the subjective and objective data for the 25 enclosures could be regarded as reliable, and representative of enclosures in general.

Since then many more measurements have been made and a comprehensive questionnaire has been issued within the B.B.C. in an attempt to collect the necessary subjective data. Relevant statistical and other techniques for analysing the results have also been studied[2, 3]. The objective measurements were carried out in the manner described in the previous report[1].

2. SUBJECTIVE INVESTIGATION.

The collection of reliable subjective data is always the most difficult aspect of acoustic investigations. It is therefore necessary to contrive carefully worded questionnaires if meaningful opinions are to be obtained. With this end in view, subjects were asked to give a numerical estimate of the following acoustic characteristics, according to the scheme outlined in Table 1, for all the enclosures which they knew.

TABLE 1

Ratings for Various Studio Characteristics

Characteristic	Class of Studio	Rating		
Overall quality		Very good (10)	Average (5)	Very bad (0)
Liveness		Much too live (10)	Correct (5)	Much too dead (0)
Bass reverberation		Much too great (10)	Correct (5)	Much too small (0)
Top reverberation		Much too great (10)	Correct (5)	Much too small (0)
Acoustic variation over floor area	Drama	Much too great (10)	Correct (5)	Much too small (0)
Naturalness	Talks and drama	Very good (10)	Average (5)	Very bad (0)
Perspective	Drama and music	Very good (10)	Average (5)	Very bad (0)
Definition	Music	Very good (10)	Average (5)	Very bad (0)
Tonal quality	Music	Very rich (10)	Average (5)	Very dry (0)
Ease of performance		Very easy (10)	Average (5)	Very difficult (0)
Ease of hearing other performers	Music	Very easy (10)	Average (5)	Very difficult (0)
Undesirable colourations		Not serious (10)		Very serious (0)
Microphone position		Not critical (10)		Very critical (0)
Cubicle acoustics		Very good (10)	Average (5)	Very bad (0)

The most important opinions required are on the overall quality of the enclosure. From these opinions some kind of collective subjective estimate of overall quality must be derived for comparison with objective measurements. In addition, detailed opinions were requested on the specific qualities mentioned, for without this information it is difficult to interpret the opinions of overall quality. It was also hoped that these detailed opinions could be correlated with parameters associated with objective measurements.

The questionnaire was circulated throughout the B.B.C., not only in London but in all the Regions. Although the forms were designed so that large numbers of opinions could be analysed by punched-card methods, the response was disappointingly small; only 117 subjects returned questionnaires. Most subjects gave an opinion on overall quality, but many of them gave opinions on only a small number of the specific qualities, so that useful results concerning the opinions of specific acoustic qualities could not be obtained.

In all previous investigations of this nature, both here and abroad, the greatest difficulty has been to obtain any correlation between the different regions of a country, because so few subjects know a sufficiently high proportion of the enclosures. As it turned out in this investigation also, only a few subjects could comment on any enclosures outside their own particular region. Fortunately, in the B.B.C., there is a small group who can reasonably be called acoustic experts (which includes the individuals whose subjective estimates of quality were used in the earlier investigation of Reference 1) who know the principal studios and concert halls in the British Isles. As a last resort it was therefore decided to analyse the overall-quality data from the 117 subjects and compare it with the opinions of the experts to see if the agreement was good. A correlation coefficient of 0·66 was obtained between the mean overall-quality value given by the experts and the mean overall-quality value given by the ordinary subjects. This is sufficient to indicate reasonable agreement between the majority of the subjects and the experts, who in these circumstances provide adequate cross correlation between the various regions. The results from all regions were therefore pooled.

3. RELATION BETWEEN SUBJECTIVE AND OBJECTIVE PARAMETERS.

At the time of the previous investigation[1], values of the decay irregularity D, the reverberation irregularity R and the mean reverberation time T_m were known for some 25 enclosures of various sizes; the subjective overall qualities, as then assessed, varied considerably. It was noticed that if $D + R$ was plotted against T_m, there was a "corridor" which, roughly speaking, included the good studios but not the others. Thereafter, a linear regression formula for $(D + \alpha R)$ on T_m was found, with α left unspecified, for six good enclosures. If this regression formula is

$$D + \alpha R = A(\alpha) + T_m B(\alpha) \qquad (1)$$

and we define

$$X(\alpha) = \frac{D + \alpha R}{A(\alpha) + T_m B(\alpha)} \qquad (2)$$

then $X(\alpha)$ will be near 1 for the six good enclosures and may have any value for the remainder. It was found that if $\alpha = 0{\cdot}7$, not only were the values of $X(0{\cdot}7)$ sufficiently close to 1 for these six enclosures, but also the values of $X(0{\cdot}7)$ for other enclosures were mostly between ~~these limits~~ 0·8 and 1·1 if the enclosure was good and outside these limits otherwise. $A(0{\cdot}7)$ was found to be 3·39 and $B(0{\cdot}7)$ was 1·43.

In the analysis of the new data a revised subjective assessment Z of overall quality was obtained, based on a suitable combination of opinions given in the questionnaire and of the opinions of the experts. A regression formula was then obtained for Z on D, R, T_m and $V^{1/3}$, V being the volume which was not taken into consideration in the earlier investigation. The result, for the 43 studios for which values of Z, D, R, T_m and V were all available, was

$$Z = -0{\cdot}439D - 0{\cdot}003321R + 2{\cdot}291T_m - 0{\cdot}007735V^{1/3} - 0{\cdot}692 \qquad (3)$$

The values of Z, D, R, T_m and $V^{1/3}$ for the 43 studios are given in Table 2. As the range of $V^{1/3}$ is large, the smallness of the coefficient of $V^{1/3}$ is more apparent than real, but the coefficient of R is remarkably small, and this is at variance with the known marked effects of an irregular reverberation-time/frequency characteristic, e.g. "boominess" or "sibilance", both of which tend to be associated with low values of R.

TABLE 2

Objective Parameters D, R, T_m and $V^{1/3}$ and Quality-parameter Z for 43 enclosures

Number and Name	D	R	T_m	$V^{1/3}$	Z
1 Aeolian 2	2·55	9	0·58	20·8	−0·45
2 B.H. 3A	3·4	7	0·59	21·10	−2·27
3 B.H. 3B	3·9	2	0·38	10·83	−1·30
4 B.H. 3C	1·95	−2	0·38	10·91	−1·82
5 B.H. 3D	3·1	1	0·37	11·24	−2·50
6 B.H. 3E	3·4	0	0·62	18·80	−4·88
7 B.H. 6C	2·4	5	0·335	16·98	3·09
8 Egton 3G	3·5	1	0·305	11·64	0·83
9 Maida Vale 1	2·7	3	1·66	61·27	3·50
10 Maida Vale 2	3·4	2	1·22	39·15	0·84
11 Maida Vale 3	3·1	3	1·24	39·15	−2·26
12 Maida Vale 5	3·35	6	0·59	29·12	1·17
13 Portland Place 1	2·0	4	0·35	17·14	−1·74
14 Portland Place 2	3·1	1	0·42	14·26	−2·83
15 Portland Place 3	3·1	4	0·57	18·47	−0·14
16 Portland Place 4	2·0	4	0·49	17·43	−2·63
17 Portland Place 5	2·5	3	0·51	17·86	−0·25
18 Concert Hall B.H.	2·7	4	1·38	50·00	2·55
19 Camden Theatre	3·1	6	1·42	68·68	0·02
20 Criterion	3·3	3	1·64	43·09	1·39
21 Paris Cinema	2·8	4	1·14	31·07	0·55
22 R.F.H.	3·4	8	1·8	90·86	−0·97
23 Bush House 11	2·95	2·5	0·38	12·64	−1·29
24 Bush House 20	3·15	2	0·385	14·88	−0·59
25 Birmingham 4	2·8	6	0·98	32·08	−1·96
26 Birmingham Vestry	2·5	8	1·26	38·70	1·39
27 Belfast 1	2·8	3	1·17	42·17	0·53
28 Belfast 5	3·0	1	0·605	18·85	0·21
29 Belfast 8	3·2	8	1·15	31·01	−0·67
30 Manchester 1	3·1	12	1·16	33·62	−0·67
31 Manchester Free Trade	2·7	6	1·93	86·62	1·48
32 Manchester Milton	3·3	3	1·65	45·33	1·83
33 Liverpool Philharmonic	2·65	4	1·65	78·02	1·05
34 Edinburgh 1	3·3	3	1·2	51·68	0·77
35 Edinburgh 5	2·9	6	0·40	12·7	−2·18
36 Edinburgh Usher	4·1	3	2·15	81·43	2·50
37 Glasgow 1	3·3	3	2·15	81·43	2·50
38 Glasgow 2	3·3	11	1·10	28·64	0·04
39 Glasgow 8	2·3	4	0·42	14·26	1·63
40 Glasgow St. Andrews	3·4	6	2·6	84·34	4·46
41 Bristol 1	3·1	6	0·96	38·70	−2·60
42 Bristol 5	3·05	4	0·60	16·87	0·24
43 Bristol Colston	2·7	8	2·15	76·63	1·68

A possible source of error is inherent in the present method of calculating D. D is the arithmetic mean of the decay irregularities measured at a number of arbitrarily chosen frequencies which are the same for all sizes of studios. Now in small studios the normal modes are widely separated at low frequencies, so it is possible for a particular and subjectively important normal mode to be almost entirely omitted or grossly over-emphasised because of the chance relation between the frequency of this normal mode and the nearest of the arbitrarily chosen frequencies used for calculating D. It was therefore decided to perform the analysis again, separating small studios from large ones. A studio having a volume less than 6,000 cu. ft (170 m^3) can reasonably be called small. Now it happened that 24 enclosures out of the 43 here considered had volumes over 22,000 cu. ft (623 m^3) while 14 were small. 5 had volumes between 6,000 and 11,000 cu. ft (170 and 312 m^3). Studios having volumes between 6,000 and about 10,000 cu. ft (170 and 283 m^3) are usually expected to fulfil a variety of requirements and are, therefore, known as general purpose studios. This varied use made it difficult for subjects to decide whether to give an opinion on a general-purpose studio as a talks studio or drama studio or a music studio and this difficulty was reflected in the subjective data. It was therefore decided to carry out the analysis for small studios with volumes below 6,000 cu. ft (170 m^3) and separately for large studios with volumes above 11,000 cu. ft (312 m^3). In this case, however, no results are available for studios having volumes between 11,000 and 22,000 cu. ft (312 m^3 and 623 m^3).

The linear regression formula for overall quality Z in terms of D, R, T_m and $V^{1/3}$ for large enclosures was found to be

$$Z = -0{\cdot}2205D - 0{\cdot}0871R + 3{\cdot}0046T_m - 0{\cdot}01901V^{1/3} - 1{\cdot}3561 \qquad (4)$$

It will be observed that the coefficient of R is no longer negligible and that the coefficient of $V^{1/3}$ is also increased.

The analysis for small studios produced poor correlation between the subjective and objective data, a fact which is unfortunate, but not surprising. It appears to indicate that the objective analysis of small studios done in the present manner is not reliable. Further investigation to decide whether the fault lies in the above-mentioned deficiencies in the derivation of D, or whether another parameter is required has yet to be carried out. Applying now to the new data for large studios, a slightly improved form of the technique used to obtain the criterion number X in Reference 1, so that $V^{1/3}$ is omitted, the modified criterion number X' is

$$X' = (D + 0{\cdot}3262R)/(1{\cdot}6387 + 1{\cdot}5362T_m) \qquad (5)$$

Fig. 1 shows the results plotted in the same manner as in the previous report [1]. In this case most good enclosures can be expected to have values of X' between 0·88 and 1·08. Most average enclosures have values of X' between 1·08 and 1·45, and bad enclosures have values over 1·45.

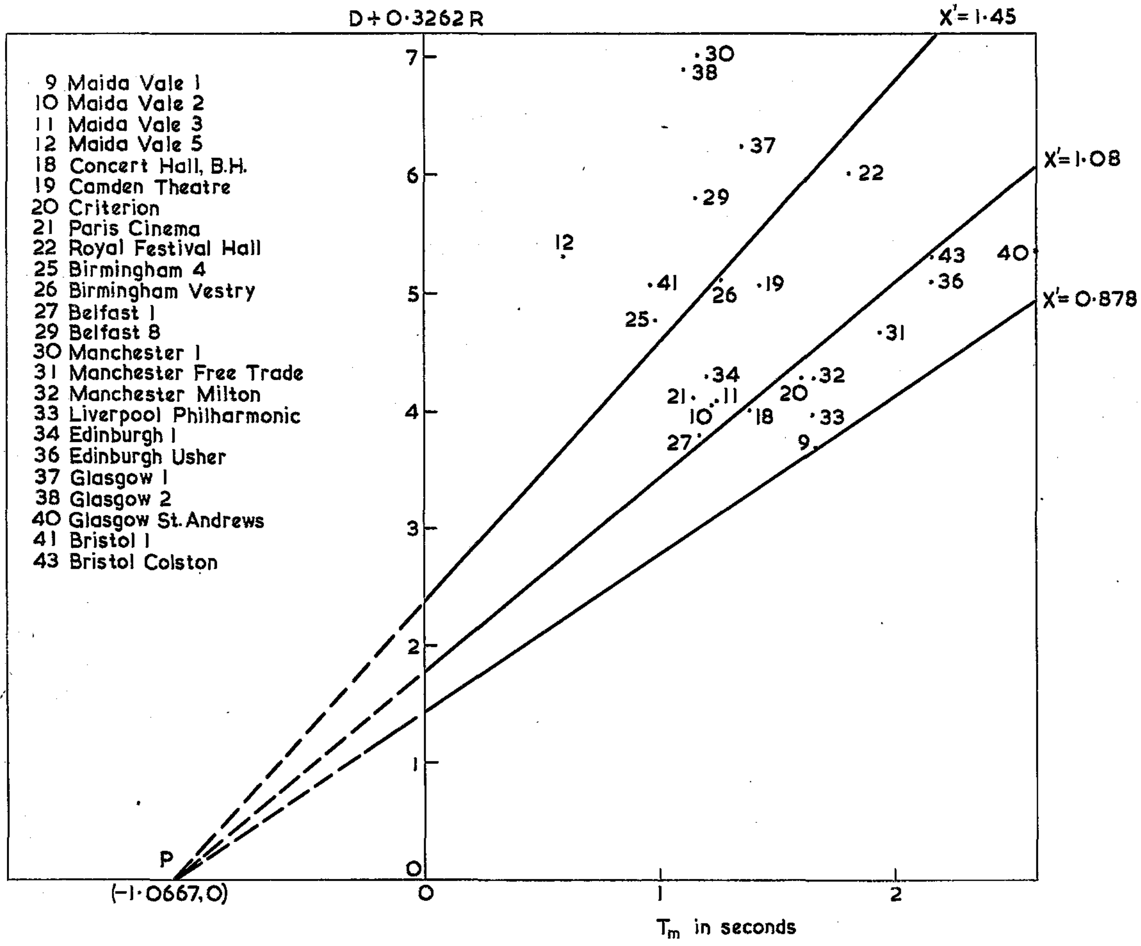

Fig. 1 - Distribution of large studios when $D+0{\cdot}3262R$ is plotted against T_m

(Studio numbers are as in Table 2)

A nomogram has been designed, as explained in Reference 4, for the graphical determination of calculated overall quality and is shown in Fig. 2; it is in fact a geometrical way of expressing the regression formula (4) for Z in terms of D, R, T_m and $V^{1/3}$ for large enclosures. As an example of the use of this nomogram consider St. Andrews Hall. First join the point $T_m = 2{\cdot}6$ to $R = 6$; this line, marked St. Andrews (1), meets the uncalibrated R_1-scale in X_1. Then join the point $D = 3{\cdot}4$ to $V^{1/3} = 84{\cdot}34$; this line, marked St. Andrews (2), meets the uncalibrated R_2-scale in Y_1. Join Y_1 X_1 and produce this line, marked St. Andrews (3) to meet the Z-scale, and read off the required value of Z, which is about 3·57 as compared with 3·58 obtained from (4) by calculation. The corresponding lines for Bristol 1 are also shown in Fig. 2.

4. COMPARISON OF CRITERIA.

In this investigation the observers were asked to rank their assessments from 0-10, although it has always been suspected that this would cause great difficulty. In contriving the original criterion it was assumed that a division into three groups, say, good, average and bad was all that was practicable. It is on this basis that

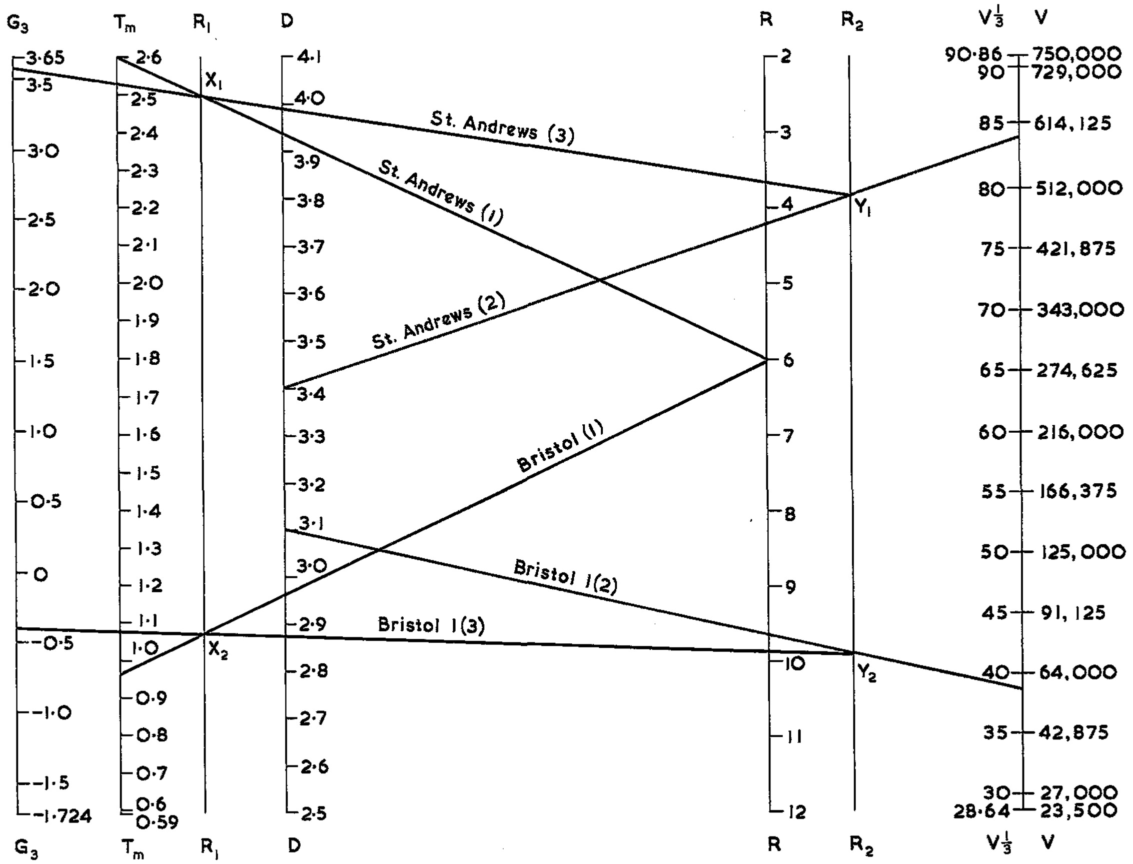

Fig. 2 - Nomogram representing regression formula (4)

Fig. 1 has been plotted. The corresponding division of the subjective quality parameter *Z* into three categories for large enclosures is somewhat arbitrary; it has been chosen so that the numbers in the three classes are as nearly equal as possible, and so as to avoid borderline cases. Table 3 shows the large enclosures (identified by the numbers used in Table 2) for which *Z* is within the limits specified at the top of the column and the modified version X' of the previous criterion is as specified at the left of the row.

TABLE 3

Three-category Comparison of *Z* and X'

	Bad *Z* ($Z < 0$)	Average *Z* ($0 < Z < 1{\cdot}45$)	Good *Z* ($Z > 1{\cdot}45$)
Good X' ($0{\cdot}88 < X' < 1{\cdot}08$)	None	Nos. 20, 33 (2 encl.)	Nos. 9, 18, 31, 32, 36, 40, 43 (7 encl.)
Average X' ($1{\cdot}08 < X' < 1{\cdot}45$)	Nos. 11, 22 (2 encl.)	Nos. 10, 19, 21, 26, 27, 34 (6 encl.)	None
Bad X' ($X' > 1{\cdot}45$)	Nos. 25, 29, 30, 38, 41 (5 encl.)	No. 12 (1 encl.)	No. 37 (1 encl.)

It is clear that the agreement between *Z* and X' is good and that to design using X' as a criterion is sufficiently accurate for most purposes. A curious result is that if a table similar to Table 3 is made with the subjective quality parameter *Z* replaced by the calculated value obtained from (4) with similar arbitrary division of the calculated values into three categories, there are only two large enclosures (Nos. 18 and 38) for which the X' category is different from the calculated-Z category. In effect, this means that the original criterion which did not take account of $V^{1/3}$ is sufficiently accurate for most purposes.

5. CONCLUSION.

This investigation indicates once again the difficulties which beset any attempts to correlate subjective with objective data. In spite of these difficulties, however, an acoustic criterion for large enclosures has been established with reasonable validity. After further investigation it will no doubt be possible to extend the criterion to cover in addition studios down to a volume of 6,000 cu. ft (170 m^3).

Further investigation, which is now proceeding, is necessary to elucidate the difficulties in the derivation of *D* for small studios having volumes below 6,000 cu. ft. It may prove to be essential to devise an additional factor to take care of the wide spacing of the normal modes at low frequencies for such studios.

Some criticism has been levelled at the criterion by Rettinger[5], on the grounds that *D*, which he considers may be a good measure of diffusion, has been merged with other parameters. It is true that *D* is a good indicator of changes in diffusion but it has so far been impossible to correlate the subjective effects of diffusion with the measurements. The reason for this is that at present the subjective effects of diffusion and reverberation cannot be separated, so that the only alternative in the light of present knowledge is to associate the objective parameters in one criterion.

6. REFERENCES.

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